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Description	

Outage Probability of Correlated Binary Source Transmission over Fading Multiple Access Channels

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***Abstract*—This paper investigates the outage behavior of transmitting correlated binary sources with arbitrary code rate over quasi-static Rayleigh fading multiple access channel (MAC). The sufficient condition for lossless communication with arbitrary code rate is obtained by assuming separate source and channel coding, which indicates the two rate regions specified by the Slepian-Wolf theorem and the MAC capacity region intersect. An upper bound of the outage probability is derived based on the sufficient condition. Asymptotic property shows the second order diversity gain can be achieved only when the tow sources are fully correlated. Numerical results demonstrate the accuracy of the derived upper bound. The ϵ-outage achievable rate, which is the largest rate of transmission such that the outage probability is smaller than a predefined ϵ value, is also analyzed. It is found the ϵ-outage achievable rate becomes lager with higher transmit power and/or stronger source correlation.**

I. Introduction

The transmission of correlated sources over a multiple access channel (MAC) is a fundamental problem with potential applications to many practical situations such as wireless sensor network (WSN) [1] and wireless mesh networks (WMN) [2]. In this problem, correlated sources are encoded by the distributed nodes that do not communicate with each other, and then transmitted simultaneously to a common receiver that intends to retrieve all the source information.

In 1980, Cover, El Gamal and Salehi [3] derived sufficient conditions of lossless communication of a pair of correlated discrete sources using joint source-channel (JSC) coding over a discrete memoryless MAC. They also showed that separate source-channel (SSC) coding is not optimal in this case by providing an interesting example. An outer bound for the capacity region of the MAC with correlated sources in finite-letter expressions was provided in [4]. A graph-based framework for transmission of correlated sources over MAC was proposed in [5] to minimize the performance loss as compared to the JSC coding scheme. The necessary and sufficient conditions for lossless transmission of correlated sources over MAC with receiver side information were characterized in [6]. Later on, Lim et al. [7] extended the results of [3] to obtain the sufficient condition for lossy communication of correlated sources over a MAC. The lossy communication of a bivariate Gaussian source over a Gaussian MAC was investigated in [8]. Sufficient conditions for transmission of correlated sources over a fading MAC with given distortions and the optimal power allocation was investigated in [9].

In the previous results, it has been implicitly assumed that the JSC codes have unit rate, i.e., the source sequences are directly and independently mapped to the channel inputs with the same length. Recently, a new JSC coding technique was proposed in [10] for transmission of two correlated sources over fading MAC, where a half-rate serial concatenated convolutional codes (SCCC) were used for JSC encoding. Since the code rate in [10] is not equal to 1, the previous results cannot be applied directly there. This motivates us to investigate the sufficient condition for correlated source transmission with arbitrary code rate over a MAC. It should be noted that since a general necessary and sufficient condition for lossless communication of correlated sources over a MAC is a long-standing open problem [11, Ch. 14.1] in Network Information Theory, the proof of the tightness of the sufficient condition is out of the scope of this paper.

In this paper, we obtain the sufficient condition for lossless communication of correlated binary sources with arbitrary code rate over fading MAC by assuming SSC coding, where the code rate is explicitly included as a parameter. As stated above, the SSC coding is not optimal in this case, therefore the sufficient condition obtained is not necessary. While the outage probability of trasmitting independent sources over fading MAC was provided in [12], [13], the outage prbability for the case with correlated sources is not well known yet. Another contribution of this paper is that we derive an upper bound of the outage probability for the case with correlated sources based on the sufficient condition obtained, which is also verified by the simulation results using the coding/decoding technique presented in [10]. The ϵ-outage achievable rate [14], which is the largest rate of transmission such that outage probability is smaller than a predefined ϵ value, is also investigated. The impact of source correlation on ϵ-outage achievable rate is illustrated.

The rest of the paper is organized as follow. In Section II, we describe the system model. The sufficient condition for lossless communication of correlated sources with arbitrary code rate over fading MAC is discussed in Section III, followed by

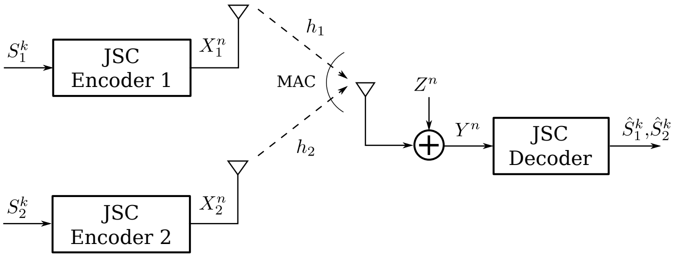

Fig. 1. Communication of two correlated sources with arbitrary code rate over a fading MAC. The source sequence S_i^k is mapped directly to the coded sequence X_i^n using a joint source channel code, $i = \{1, 2\}$. k is not necessarily equal to n.

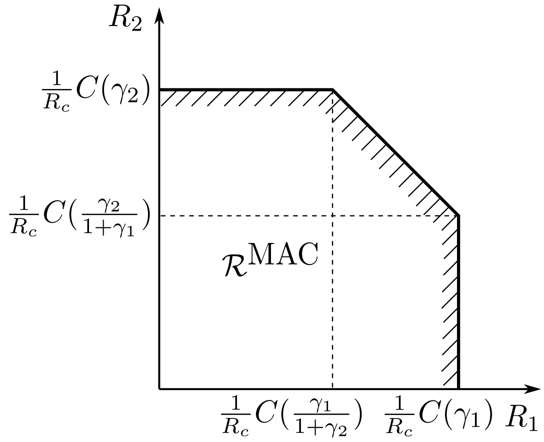

Fig. 2. Rate region constrained by the MAC capacity region.

the outage probability derivation presented in Section IV. In Section V, numerical results are provided to verify the outage analysis. Finally, conclusions are drawn in Section VI with some concluding remarks.

II. System Model

The abstract model for transmitting two correlated sources with arbitrary code rate over a fading MAC is shown in Fig. 1. Assume the two transmitters and the receiver are equipped with single antenna. Let $\{(S_1)^t\}_{t=1}^k$ and $\{(S_2)^t\}_{t=1}^k$ be stationary and memoryless sources with length k taking values from a binary set $\mathcal{S} = \{0, 1\}$. For simplicity, we denote $\{(S_1)^t\}_{t=1}^k$ and $\{(S_2)^t\}_{t=1}^k$ as S_1^k and S_2^k, respectively. Assume S_1^k is generated according to a Bernoulli distribution $\mathrm{Bern}(0.5)$, and S_2^k is the output of S_1^k over a binary symmetric channel (BSC) with crossover probability p. It is easily found $\Pr(S_1 = 0) = \Pr(S_2 = 0) = 1/2$, and hence $H(S_1) = H(S_2) = 1$. In this paper, the crossover probability p is regarded as the source correlation parameter.

At the two transmitters, S_1^k and S_2^k are encoded by two JSC encoders to obtain signal sequences X_1^n and X_2^n, respectively. The code rates of two JSC encoders are the same, which is $R_c = k/n$. Here k and n denote the length of source sequence and coded sequence, respectively. Note that R_c can take arbitrary positive value. X_1^n and X_2^n are then transmitted simultaneously to the receiver, and the received signal can be expressed as

$$y[m] = \sqrt{P_1} \cdot h_1 \cdot x_1[m] + \sqrt{P_2} \cdot h_2 \cdot x_2[m] + z[m], \quad (1)$$

where m is the time index of the signals, h_i is the channel gain between the i-th transmitter and the receiver, and $z[m]$ is a complex additive white Gaussian noise (AWGN). P_1 and P_2 denote the transmit power of the two transmitters. Without loss of generality, we normalize the noise power, i.e., $E[|z|^2] = 1$, and assume $P_1 = P_2 = P$. Since both channels between the two transmitters and the receiver experience quasi-static, independent and identically distributed (i.i.d.) Rayleigh fading, the channel gain h_i can be modeled by a complex zero-mean Gaussian variable with unit variance. Following the descriptions above, the instantaneous received signal-to-noise power ratio (SNR) for transmitter i is defined as $\gamma_i = P \cdot |h_i|^2,\ i = \{1, 2\}$.

After receiving y, the receiver performs JSC decoding to retrieve the source sequences S_1^k and S_2^k, of which estimates are denoted as $\hat{S}_1^k$ and $\hat{S}_2^k$, respectively.

III. Sufficient Condition for Reliable Transmission

Assume the JSC coding of S_1^k and S_2^k shown in Fig. 1 is performed by SSC coding. At the transmitter side, first S_1^k and S_2^k are encoded using two source encoders $\mathcal{E}_1^S(\cdot)$ and $\mathcal{E}_2^S(\cdot)$, respectively, to remove the redundancy inherent within each sequence[1]. The coded sequences are denoted as $U_1^{kR_1}$ and $U_2^{kR_2}$, where R_1 and R_2 are the code rates of $\mathcal{E}_1^S(\cdot)$ and $\mathcal{E}_2^S(\cdot)$, respectively. $U_1^{kR_1}$ and $U_2^{kR_2}$ are then encoded using two channel encoders $\mathcal{E}_1^C(\cdot)$ and $\mathcal{E}_2^C(\cdot)$ to obtain X_1^n and X_2^n, respectively. It is easy to see that the code rates of $\mathcal{E}_1^C(\cdot)$ and $\mathcal{E}_2^C(\cdot)$ are $R_1' = kR_1/n = R_1 R_c$ and $R_2' = kR_2/n = R_2 R_c$, respectively. The encoding process described above can be expressed as

$$S_1^k \to X_1^n:\ U_1^{kR_1} = \mathcal{E}_1^S(S_1^k),\ X_1^n = \mathcal{E}_1^C(U_1^{kR_1}), \quad (2)$$

and

$$S_2^k \to X_2^n:\ U_2^{kR_2} = \mathcal{E}_2^S(S_2^k),\ X_2^n = \mathcal{E}_2^C(U_2^{kR_2}). \quad (3)$$

At the receiver side, we first perform decoding of the channel codes to reconstruct $U_1^{kR_1}$ and $U_2^{kR_2}$. It is well known that the capacity region of the MAC is the set of rate pairs (R_1', R_2') such that

$$\begin{cases} R_1' &\leq& C(\gamma_1), \\ R_2' &\leq& C(\gamma_2), \\ R_1' + R_2' &\leq& C(\gamma_1 + \gamma_2), \end{cases} \quad (4)$$

where $C(x) = \log_2(1 + x)$ is the Gaussian channel capacity function. Note $R_i' = R_i R_c,\ i = \{1, 2\}$, by dividing both sides of the inequalities in (4) by R_c, we have

$$\begin{cases} R_1 &\leq& \frac{1}{R_c}C(\gamma_1), \\ R_2 &\leq& \frac{1}{R_c}C(\gamma_2), \\ R_1 + R_2 &\leq& \frac{1}{R_c}C(\gamma_1 + \gamma_2). \end{cases} \quad (5)$$

[1]Note the source encoders $\mathcal{E}_1^S(\cdot)$ and $\mathcal{E}_2^S(\cdot)$ do not communicate with each other.

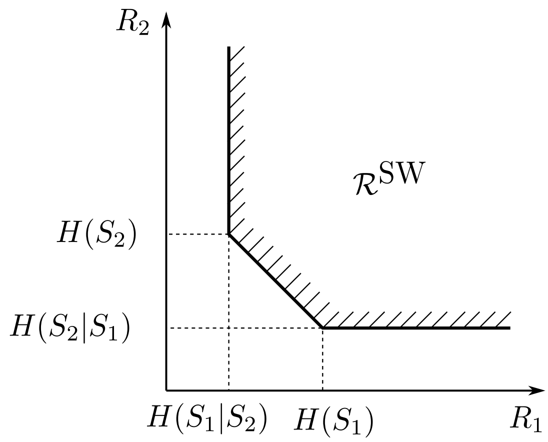

Fig. 3. Admissible rate region specified by Slepian-Wolf theorem.

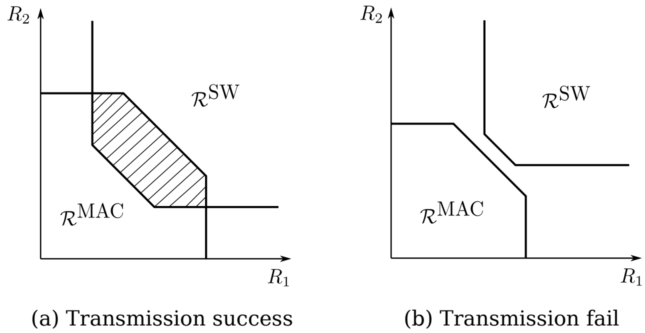

Fig. 4. $\mathcal{R}^{\text{SW}}$ and $\mathcal{R}^{\text{MAC}}$ intersection analysis, (a) an example of transmission success since $\mathcal{R}^{\text{SW}} \cap \mathcal{R}^{\text{MAC}} \neq \emptyset$, and (b) an example of transmission fail since $\mathcal{R}^{\text{SW}} \cap \mathcal{R}^{\text{MAC}} = \emptyset$.

Let $\mathcal{R}^{\text{MAC}}$ denote the rate region constrained by the MAC capacity region as shown in (5). It is shown in Fig. 2 that $\mathcal{R}^{\text{MAC}}$ is a bounded pentagon. As long as the rate pair (R_1, R_2) falls inside $\mathcal{R}^{\text{MAC}}$, $U_1^{kR_1}$ and $U_2^{kR_2}$ can be recovered with arbitrary small probability of error.

Assume $U_1^{kR_1}$ and $U_2^{kR_2}$ are recovered successfully after channel decoding and passed to the source decoder. The next step is to recover S_1^k and S_2^k based on $U_1^{kR_1}$ and $U_2^{kR_2}$. This problem falls into the category of distributed lossless source coding. According to the Slepian-Wolf theorem [15], the admissible rate region $\mathcal{R}^{\text{SW}}$ is the set of rate pairs (R_1, R_2) that satisfy the following inequalities

$$\left\{ \begin{array}{rcl} R_1 & \geq & H(S_1|S_2), \\ R_2 & \geq & H(S_2|S_1), \\ R_1 + R_2 & \geq & H(S_1, S_2), \end{array} \right. \tag{6}$$

which is depicted in Fig. 3. As can be seen from the figure, $\mathcal{R}^{\text{SW}}$ is an unbounded polygon. Since both S_1 and S_2 are binary source and they are bit-flipped versions of each other, it is obvious that $H(S_1|S_2) = H(S_2|S_1) = H_b(p)$ and $H(S_1, S_2) = 1 + H_b(p)$, where $H_b(x) = -x\log_2 x - (1-x)\log_2(1-x)$ is the binary entropy function.

It is clear that to guarantee error free transmission using the SSC coding, both the conditions in (5) and (6) should be satisfied. By combining (5) and (6), we obtain the conditions for lossless communication of S_1^k and S_2^k over the MAC, expressed as

$$\left\{ \begin{array}{rcl} H(S_1|S_2) & \leq & \frac{1}{R_c}C(\gamma_1), \\ H(S_2|S_1) & \leq & \frac{1}{R_c}C(\gamma_2), \\ H(S_1, S_2) & \leq & \frac{1}{R_c}C(\gamma_1 + \gamma_2). \end{array} \right. \tag{7}$$

It should be emphasized here that since using SSC coding for transmitting correlated sources over a MAC is *not* optimal in general, (7) is *only* a sufficient condition but not a necessary condition for lossless communication of S_1^k and S_2^k using JSC coding with code rate R_c over the MAC. Note also that the sufficient condition does not gaurantee the existence of JSC code, however, it can be used to upper bound the outage probability as shown in Section IV.

IV. Outage Probability Analysis

As indicates in (7), if $\mathcal{R}^{\text{SW}}$ and $\mathcal{R}^{\text{MAC}}$ intersect with each other as shown in Fig. 4(a), reliable transmission can be achieved. In other words, if $\mathcal{R}^{\text{SW}}$ and $\mathcal{R}^{\text{MAC}}$ do not intersect, as shown in Fig. 4(b), a transmission failure will occur. Therefore the outage event of the system is defined as $\mathcal{R}^{\text{SW}} \cap \mathcal{R}^{\text{MAC}} = \emptyset$. The outage probability is then defined as

$$P_{\text{out}} = 1 - P_{\text{in}}, \tag{8}$$

where $P_{\text{in}} = \Pr\{\mathcal{R}^{\text{SW}} \cap \mathcal{R}^{\text{MAC}} \neq \emptyset\}$. We define $\lambda_i = |h_i|^2$, therefore $\gamma_i = P\lambda_i,\ i \in \{1, 2\}$. According to the block Rayleigh fading assumption, λ_i is i.i.d. exponential variables with unit mean. With this definition, P_{in} can be further expressed as

$$\begin{aligned} P_{\text{in}} = \Pr\Big\{ & H_b(p) \leq \frac{1}{R_c}\log_2(1 + P\lambda_1), \\ & H_b(p) \leq \frac{1}{R_c}\log_2(1 + P\lambda_2), \\ & 1 + H_b(p) \leq \frac{1}{R_c}\log_2[1 + P(\lambda_1 + \lambda_2)] \Big\} \\ = \Pr\Big\{ & \lambda_1 \geq \frac{2^{R_cH_b(p)} - 1}{P}, \lambda_2 \geq \frac{2^{R_cH_b(p)} - 1}{P}, \\ & \lambda_1 + \lambda_2 \geq \frac{2^{R_c[1+H_b(p)]} - 1}{P} \Big\} \\ = & \int_{\frac{2^{R_cH_b(p)}-1}{P}}^{\frac{2^{R_cH_b(p)}(2^{R_c}-1)}{P}} \int_{\frac{2^{R_c[1+H_b(p)]}-1}{P}-\lambda_1}^{+\infty} e^{-(\lambda_1+\lambda_2)} d\lambda_2 d\lambda_1 \\ & + \int_{\frac{2^{R_cH_b(p)}(2^{R_c}-1)}{P}}^{+\infty} \int_{\frac{2^{R_cH_b(p)}-1}{P}}^{+\infty} e^{-(\lambda_1+\lambda_2)} d\lambda_2 d\lambda_1 \\ = & e^{-\frac{2^{R_c[1+H_b(p)]}-1}{P}} \{1 + \frac{2^{R_cH_b(p)}(2^{R_c}-2)+1}{P}\}. \end{aligned} \tag{9}$$

Note the outage probability P_{out} in (8) is derived based on the sufficient condition for lossless communication of S_1^k and S_2^k over the MAC, therefore it is an upper bound of the outage probability of the system. In the special case that the two sources are independent ($p = 0.5$), P_{out} is the same as the result presented in [12, Eq. (20)], where the exact outage probability of two independent sources over fading MAC is derived. This indicates the sufficient condition becomes tight when the two sources are independent.

A. Asymptotic Property

By using the Taylor expansion

$$e^{-x} = \sum_{n=0}^{\infty} \frac{(-x)^n}{n!} \approx 1 - x, \text{ as } x \to 0, \tag{10}$$

P_{out} in (8) can be approximated as

$$P_{\text{out}} \approx \frac{2^{1+R_c H_b(p)} - 2}{P} + \frac{\psi(R_c, p)}{P^2}, \tag{11}$$

where $\psi(R_c, p) = (2^{R_c[1+H_b(p)]} - 1)[2^{R_c H_b(p)}(2_c^R - 2) + 1]$, as $P \to \infty$.

In the case that the two sources are fully correlated ($p = 0$), the first term in (11) equals 0, P_{out} can be further expressed as

$$P_{\text{out}} \approx \frac{\psi(R_c, 0)}{P^2}, \tag{12}$$

where $\psi(R_c, 0) \neq 0$. Clearly, as $P \to \infty$, P_{out} is inversely proportional to P^2, which indicates the outage probability exhibits the second order diversity.

On the other hand, if the two sources are not fully correlated ($p \neq 0$), P_{out} in (11) is dominated by the first term as

$$P_{\text{out}} \approx \frac{2^{1+R_c H_b(p)} - 2}{P}. \tag{13}$$

In this case, as $P \to \infty$, P_{out} is inversely proportinal to P, therefore no diversity gain can be achieved.

B. ϵ-outage Achievable Rate

With the outage probability viewed as a function of R_c and p, we define the ϵ-outage achievable rate as

$$R_c^{\epsilon}(p) = \sup\{R_c : P_{\text{out}}(R_c, p) \leq \epsilon\}. \tag{14}$$

This is the largest rate of transmission such that the outage probability $P_{\text{out}}(R_c, p)$ is not larger than ϵ.

V. Numerical Results and Discussion

In this section, we present numerical results to verify the accuracy of the upper bound of the outage probability. The code rate is set at $R_c = 1/2$.

The outage probability P_{out} versus the transmit power P is shown in Fig. 5. The outage probability curves of maximal-ratio combining (MRC) [16, Ch. 7.2.4] with no diversity ($N = 1$) and with the second order diversity ($N = 2$) are also provided as a reference. As can been seen from the figure, if $p = 0$, P_{out} is exactly the same as that with MRC, exhibiting the second order diversity. As p grows, P_{out} also increases. For $p = 0.01$, P_{out} exhibits second order diversity in low SNR region, but asymptotically converges to no diversity in high SNR region. For $p = 0.1$, P_{out} is very close to MRC with no diversity. Finally, if $p = 0.5$, P_{out} has no diversity, however it is larger than that with MRC with no diversity. This is because P_{out} is defined as the probability of at least one of the two sources can not be correctly recovered at the receiver.

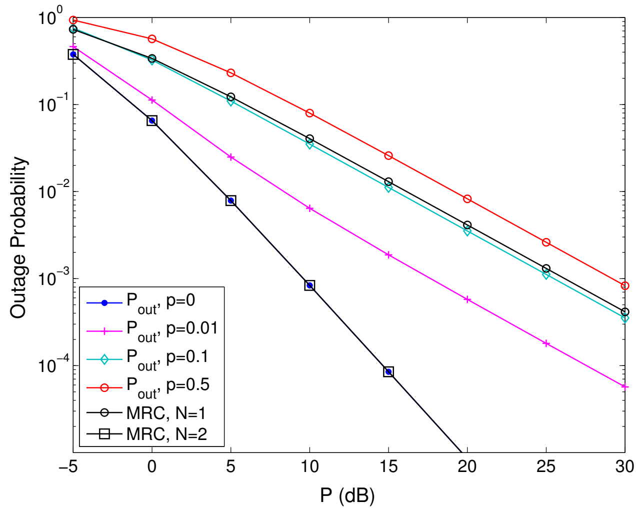

Fig. 5. Performance comparison with MRC.

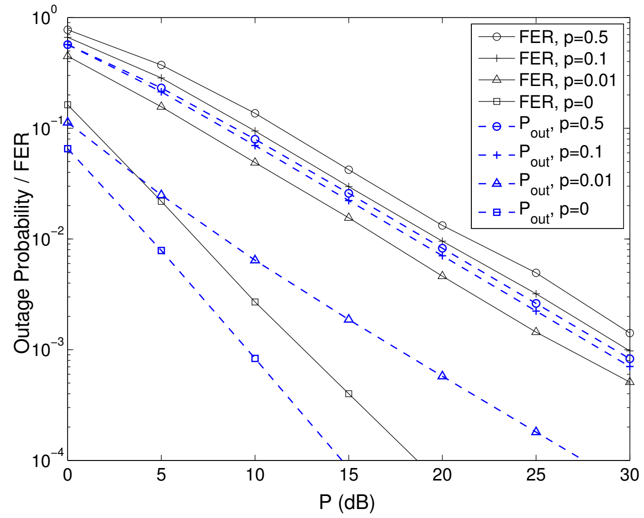

Fig. 6. Comparison between theoretical outage probability and simulated FER performance.

It should be emphasized that with large P value, the second order diversity can be achieved only if $p = 0$, this is consistent with the asymptotic analysis.

Fig. 6 shows the comparison between P_{out} and FER performance obtained by computer simulations using the technique presented in [10]. In the simulations, the block length is set at $k = 10,000$, and in total $100,000$ different blocks were transmitted from each transmitter. It is shown that for different p values, the FER curve has the same tendency as the P_{out} curve. However, since the codes used in [10] are not capacity-achieving for $R_c = 1/2$, there is a gap between the FER and P_{out} curves. The gaps are around $2-3$ dB for $p = 0, 0.1$, and 0.5, while the gap is around 8 dB[2] for $p = 0.01$. This observation indicates that although P_{out} is an upper bound

[2]The gap is also largely due to the fact that [10] assumes binary coding, while this paper assumes Gaussian codebook, both for the channel code.

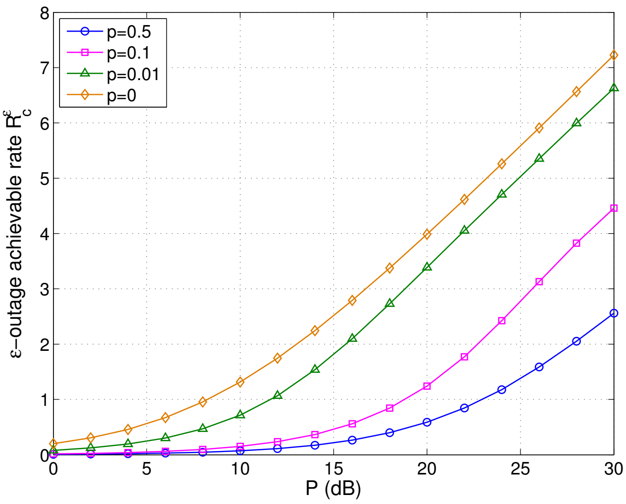

Fig. 7. The ϵ-outage achievable rate as a function of P and p, where $\epsilon = 0.01$.

of the outage probability, it can be used as an reference in practical design of coding/decoding chain for transmitting correlated sources over fading MAC.

The ϵ-outage achievable rate versus the transmit power P is shown in Fig. 7, where $\epsilon = 0.01$. It is observed that for the same p value, R_c^ϵ increases as the transmit power P increases. Another interesting observation is that for the same P value, R_c^ϵ also increases as p decreases (the source correlation becomes stronger). This can be understood from the SSC coding point of view. Larger transmit power enables to use higher rate channel code, while stronger source correlation enables to remove more redundancy after source encoding[3], both of which result in the increased R_c^ϵ.

VI. Conclusions

In this paper, lossless communication of two correlated binary sources with arbitrary code rate over fading MAC was investigated. The sufficient condition for lossless communication was obtained by assuming SSC coding, which is not strictly tight because of the suboptimality of SSC coding. The outage event was formulated based on the sufficient condition, and an upper bound of the outage probability was calculated. It was shown through asymptotic analysis that the second order diversity can be achieved only if the two sources are fully correlated. Numerical results were provided to confirm the accuracy of the upper bound and the asymptotic property. It was also demonstrated that the ϵ-outage achievable rate increases as the transmit power increases and/or the source correlation becomes stronger. The outage probability provided in this paper can be used in designing new coding/decoding schemes for transmitting correlated sources with arbitrary code rate over fading MAC. Replacing the Gaussian capacity by the constellation constrained capacity (CCC) for finite alphabet transmission is left as a future study.

[3]As noted before, the source encoders can remove redundancy without communicating with each other, according to the Slepian-Wolf theorem.

Acknowledgement

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